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14. ABSTRACT
Integration of active fluids and robotics holds the potential to launch a novel class of compliant mechanisms and mesoscale hydraulic robots. The incorporation of “active,” “field-activated,” or “field-responsive” fluids – i.e. fluids that change their material properties in response to an applied field – into traditional robotic components offers a number of compelling advantages over existing technologies. In this project we develop MINERVA (Multichannel INtegrated ER Valve Assemblies), a small-scale electrorheological (ER) servovalve that holds the

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Final Report: Enabling Novel Minimally-Actuated Robotic Capabilities Through Active Fluids

## ABSTRACT

Integration of active fluids and robotics holds the potential to launch a novel class of compliant mechanisms and mesoscale hydraulic robots. The incorporation of "active," "field-activated," or "field-responsive" fluids – i.e. fluids that change their material properties in response to an applied field – into traditional robotic components offers a number of compelling advantages over existing technologies. In this project we develop MINERVA (Multichannel INtegrated ER Valve Assemblies), a small-scale electrorheological (ER) servovalve that holds the potential to unleash a new class of affordable small-scale hydraulic systems. This report summarized the underlying science, valve fabrication, and integration of MINERVA into robotic platforms. In addition we investigate the use of active materials in jammable robotic systems and adhesive climbers.

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## Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

### (a) Papers published in peer-reviewed journals (N/A for none)

| Received | | Paper |
|---|---|---|
| 07/18/2013 | 8.00 | Gareth H. McKinley, Randy H. Ewoldt, Piotr Tourkine, A. E. Hosoi. Controllable adhesion using field-activated fluids, Physics of Fluids, (07 2011): 73104. doi: 10.1063/1.3608277 |
| 07/18/2013 | 7.00 | Bian Qian, Gareth H. McKinley, A. E. Hosoi. Structure evolution in electrorheological fluids flowing through microchannels, Soft Matter, (01 2013): 2889. doi: 10.1039/c2sm27022f |

**TOTAL:** 2

**Number of Papers published in peer-reviewed journals:**

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### (b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

**TOTAL:**

**Number of Papers published in non peer-reviewed journals:**

---

### (c) Presentations

1. Ahmed Helal. Society of Rheology Meeting, Feb 2013, "Design of Integrated ER valves"

2. Boston Dynamics Active Fluids Program: IEEE RAS Chapter, 9/11/2012

**Number of Presentations:** 0.00

## Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | | Paper |
|---|---|---|
| 10/05/2012 | 1.00 | Nadia G. Cheng , Maxim B. Lobovsky, Steven J. Keating, Adam M. Setapen, Katy I. Gero, Anette E. Hosoi, Karl D. Iagnemma. Design and Analysis of a Robust, Low-cost, Highly Articulated Manipulator Enabled by Jamming of Granular Media, 2012 IEEE International Conference on Robotics and Automation, St. Paul, MN, 2012. , . : , |

**TOTAL:** **1**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | | Paper |
|---|---|---|
| 07/18/2013 | 5.00 | M. Watanabe, N. Wiltsie, A. E. Hosoi, K. Iagnemma. Characteristics of Controllable Adhesion using Magneto-Rheological Fluid and its Application to Climbing Robotics, Proceedings of the IEEE International Conference on Robots and Systems, 2013. , . : , |
| 10/09/2012 | 3.00 | Nicholas Wiltsie, Michele Lanzetta, Karl Iagnemma. A Controllably Adhesive Climbing Robot Using Magnetorheological Fluid, Technologies for Practical Robotics (TePRA) 2012. 2012/04/23 00:00:00, . : , |

**TOTAL:** **2**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## (d) Manuscripts

| Received | | Paper |
|---|---|---|
| 10/05/2012 | 2.00 | Gareth H. McKinley, Anette Hosoi, Bian Qian. Structure evolution in electrorheological fluids flowing through microchannels, Soft Matter (08 2012) |

**TOTAL:** **1**

**Number of Manuscripts:**

## Books

Received Paper

**TOTAL:**

## Patents Submitted

1. Printed Circuit Board Electrorheological Fluid Valve (to be forwarded to contracting officer)

2. Cheng, N., Lobovsky, M., Hosoi, A., and Iagnemma, K., "Continuum Style Manipulator Actuated with Phase Change Media," US patent application PCT/US13/30354 filed April, 2013.

3. Wiltsie, N., Iagnemma, K., Hosoi, A., Ewoldt, R., and McKinley, G., "Magnetorheological Fluid Adhesion-Based Climbing and Gripping," US provisional patent application filed June, 2012.

## Patents Awarded

## Awards

Hosoi: SIAM Block Lecture (2013)
Hosoi: Fellow of the American Physical Society (2012)

## Graduate Students

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Nadia Cheng | 0.80 | |
| Ahmed Helal | 0.80 | |
| **FTE Equivalent:** | **1.60** | |
| **Total Number:** | **2** | |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| QIan Bian | 1.00 |
| **FTE Equivalent:** | **1.00** |
| **Total Number:** | **1** |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
|---|---|---|
| Anette Hosoi | 0.04 | |
| **FTE Equivalent:** | **0.04** | |
| **Total Number:** | **1** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Julie Wang | 1.00 | Mechanical Engineering |
| Michael Buchman | 0.00 | Mechanical Engineering |
| **FTE Equivalent:** | **1.00** | |
| **Total Number:** | **2** | |

## Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ...... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

## Names of Personnel receiving masters degrees

| NAME | |
|---|---|
| Nicholas Wiltsie | |
| **Total Number:** | **1** |

## Names of personnel receiving PHDs

| NAME | |
|---|---|
| Nadia Cheng | |
| **Total Number:** | **1** |

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|---|---|
| Karl Iagnemma | 0.20 |
| **FTE Equivalent:** | **0.20** |
| **Total Number:** | **1** |

## Sub Contractors (DD882)

1 a. Boston Dynamics

1 b. 78 Fourth Avenue

Waltham MA 02451-7507

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):** System integration. Prototype development of ER hydraulic systems

**Sub Contract Award Date (f-1):** 6/15/2011 12:00:00AM

**Sub Contract Est Completion Date(f-2):** 6/14/2013 12:00:00AM

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## Inventions (DD882)

## Scientific Progress

See Attachement.

## Technology Transfer

Massachusetts Institute of Technology

# M3 FINAL REPORT:
## Enabling Novel Minimally-Actuated Robotic Capabilities through Active Fluids

**PIs**: A. E. Hosoi (MIT) and Mike Murphy (BDI)
**Report Period**: June 15, 2011 – June 14, 2013

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**List of Appendixes, Illustrations and Tables**.

**Statement of the problem studied.**

Integration of active fluids and robotics holds the potential to launch a novel class of compliant mechanisms and mesoscale hydraulic robots. The incorporation of "active," "field-activated," or "field-responsive" fluids – i.e. fluids that change their material properties in response to an applied field – into traditional robotic components offers three compelling advantages over existing technologies.

1. The benefits of hydraulic systems may be realized at smaller size-scales than has been traditionally possible, potentially filling the gap between conventional hydraulic robots and mesoscale systems, where electromagnetic actuation is currently the primary technology.
2. Active fluids can act as adhesives, enabling climbing devices. Adhesive locomotion, a crawling strategy adopted by a number of biological systems, has several advantages over more traditional modes of travel including increased stability, mechanical simplicity, versatility and dramatically simplified traction control.
3. Active fluids may be incorporated into a soft skeleton creating a structure with locally tunable stiffness. This in turn enables highly deformable components characterized by a large number of degrees of freedom that can be realized with a relatively small number of actuators.

*Meso- and microscale hydraulics.* Robots that utilize fluid power such as Big Dog have demonstrated impressive locomotion capabilities. In a fluid-powered robot system, a large centralized power source (pump) distributes power to small, lightweight but high force actuators throughout the robot. The advantages of this type of system include high force density actuators, joint locking, and the ability to size the power system for intermittent actuator usage rather than peak power.

> **Mechanical servovalves – a critical component in hydraulic systems – do not scale favorably to smaller sizes due to their mechanical complexity and required fabrication tolerances. This limitation prevents the use of hydraulic power in robots under a certain size. Additionally, high performance hydraulic servovalves can be extremely expensive, pushing up robot cost with each degree of freedom. To address this issue, we propose to implement electrorheological (ER) valves to replace traditional servovalves in hydraulic systems, where the hydraulic fluid would be the ER fluid itself.**

> **The centerpiece of our program is the development of hydraulically-powered, small-scale, robotic systems using electrorheological fluids. The advantage of this approach is that the same fluid can be used for power distribution, structural stiffness, adhesion, and internal valving and, by using a field responsive fluid, it can all be done without mechanical valving or dynamic seals. We envision that these technological advances will enable novel robotic capabilities and catalyze the next generation of small, cheap – even disposable "no serial number" – robots.**

ER fluids contain a suspension of small dielectric particles; in the presence of an applied electric field, the particles form chains, dramatically changing the material properties of the fluid. These chains can be used to form fast-acting valves and clutches without the use of moving mechanical components. Traditional hydraulic servovalves, which contain electromagnetic coils and moving parts, are relatively heavy and cannot easily be miniaturized. As a consequence, increasing the number of valves in a small robot system quickly results in a significant rise in the proportion of valve mass to robot mass. In contrast, an ER valve can be made up from a simple sandwich of electrodes, which can be fabricated at any scale using various fabrication methods, including printed circuit boards, and MEMS techniques. These valves do not contain large masses of metal so they are lightweight, and can be integrated into the hydraulic lines as part of the fluid power distribution system. Their simple and light-weight construction makes adding a new valve "cheap," in the sense of cost of production, weight, and integration complexity of the system. Additionally, due to their simple construction, ER valves can be fabricated at much smaller scales, allowing integration into milli-scale and micro-scale systems. ER valves are extremely low power devices, as current is not required for steady state operation. Only a small leakage current prevents the valves from being completely bi-stable. These characteristics make ER fluids very attractive for use in small, high DOF robots.

Our research program contained a mix of fundamental research in fluid mechanics, robotics and manufacturing – in which we develop the underlying scientific concepts and design rules associated with active fluid robotic systems and components – and technology development in which we will apply these concepts in the design and construction of small-scale prototype hydraulic robot systems.

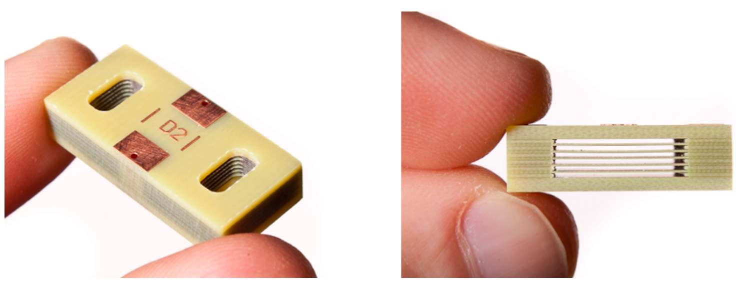



Figure 1: Fabricated MINERVAs (Multichannel INtegrated ER Valve Assemblies).

**Summary of the most important results**.

> **Our key advance is the development of MINERVA (Multichannel INtegrated ER Valve Assemblies) shown in Figure 1. In order to decrease part count, assembly time, cost, and improve package density and quality control, we have developed a process that enables us to fabricate valves that are manufacturable with only minor modifications to the standard PCB (Printed Circuit Board) fabrication process. With this new process, we are able to design ER valves in CAD, and receive them back from the**

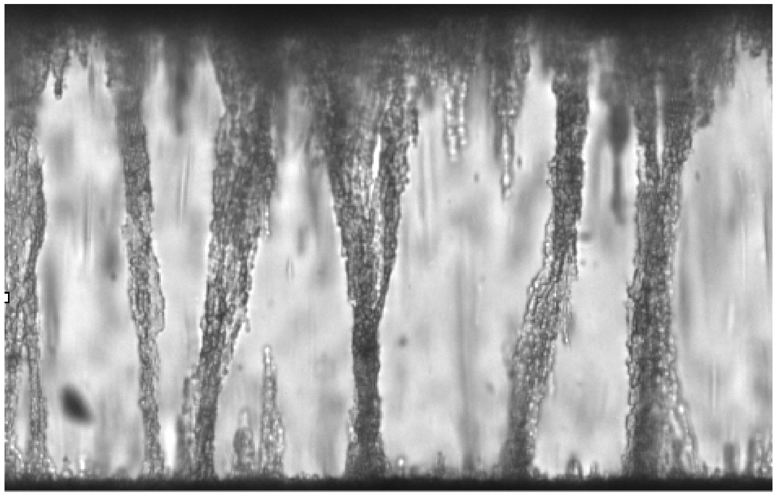


Figure 2: Particle structures observed via high-speed microscopic imaging in activated ER fluids in flow visualization channels.

> **board shop completely ready for operation. This procedure, reduces the total cost per valve to approximately $5, compared with existing small-scale servovalve technology which costs on the order of $1000-$10,000 *per valve* for comparably sized valves. These new MINERVAs have the potential to unleash a new class of affordable small-scale hydraulic systems.**

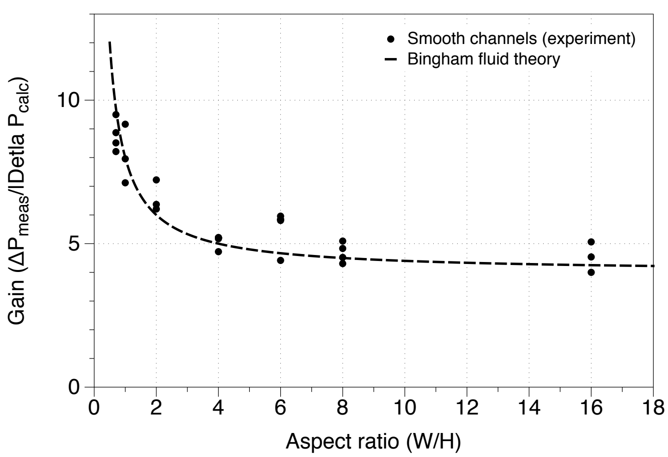
**Supporting advances:**

The new MINERVA technology would not have been possible without a host of accompanying fundamental scientific advances. These include:

1. *High-speed microscopic imaging of structure formation in channels.* To gain insights essential to the development of accurate models of ER flow in channels, we designed and built an apparatus that allows us to visualize particle chain formation in activated ER fluids. Figure 2 shows a sample image obtained from our setup. One of the key discoveries resulting from this visualization is that there are two types of structures that form in the channels: a uniform layer of particles that builds up on the electrodes and the formation of channel-spanning particle chains. The critical voltage required to arrest fluid flow is primarily determined by this mechanism of particle layer formation [5].

2. *Effect of channel aspect ratio.* One parameter that was found to significantly affect the holding pressure (and hence valve strength) is the channel cross-section aspect ratio $W/h$, where $W$ is the width of the channel and $h$ is the height. To estimate the holding strength of the valve, we model the ER fluid as a simple Bingham plastic fluid with a field-dependent yield stress and a plastic viscosity. Theoretically, in the limit of large aspect ratios, the holding pressure is given by $\Delta P = 2\tau_y L/h$. The exact expression for finite aspect ratios cannot

be computed analytically but is expected to depend on the dimensionless parameter $W/h$. In order to determine this dependence, we fabricated smooth channels with cross-sectional aspect ratios varying from 0.7 to 16, and tested the holding pressure at different electric fields. Figure 3 [Left] shows the measured holding pressure normalized by the theoretical holding pressure from the infinite aspect ratio Bingham model. An increase of the holding pressure with the decreasing aspect ratio was observed. To understand the increase in holding strength at low aspect ratio, we consider an analogy with Newtonian channel flow and substitute $D_H$, the hydraulic diameter, for $h$ in the expression for the holding pressure. The definition converges to the appropriate analytic limits for very large or very small aspect ratios, and to the Newtonian flow expression in the no field case. This new model, combined with expressions for the viscous dissipation in the channels, allows us to formulate design rules for optimal channel widths in our valves.



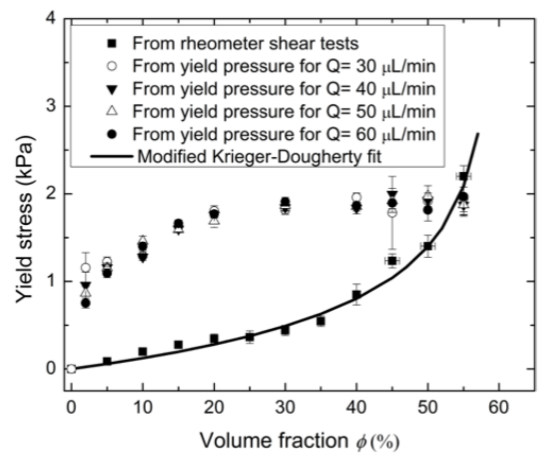




Figure 3: [Left] Measured data for holding pressure for various aspect ratio channels (solid points). Modified Bingham model using the hydraulic diameter as the relevant length scale (dashed line). [Right] Yield stress in shear and flow modes as a function of initial volume fraction of particles, $\phi$. In shear mode $\phi$ is conserved whereas in flow mode, particles pile up at the channel entrance resulting in a higher effective yield stress.

3. *"Shear mode" versus "Flow mode."* A number of groups have reported a discrepancy between tests associated with open systems (Flow mode) and rheometry tests associated with closed systems (Shear mode). This discrepancy is remarkably consistent. We observe a factor of four increase in holding strength in our channels compared to the predicted strength from rheology data and similar findings have been reported in the literature. The origin of this discrepancy, which was revealed in our visualization studies, is the dynamically determined particle volume fractions in open system (as opposed to closed systems where the total number of particles is conserved). In the open channels, the volume fraction of particles locally increases at the inlet until it reaches the amorphous maximum packing volume fraction thus increasing the yield stress of the fluid (see Figure 3) [4].

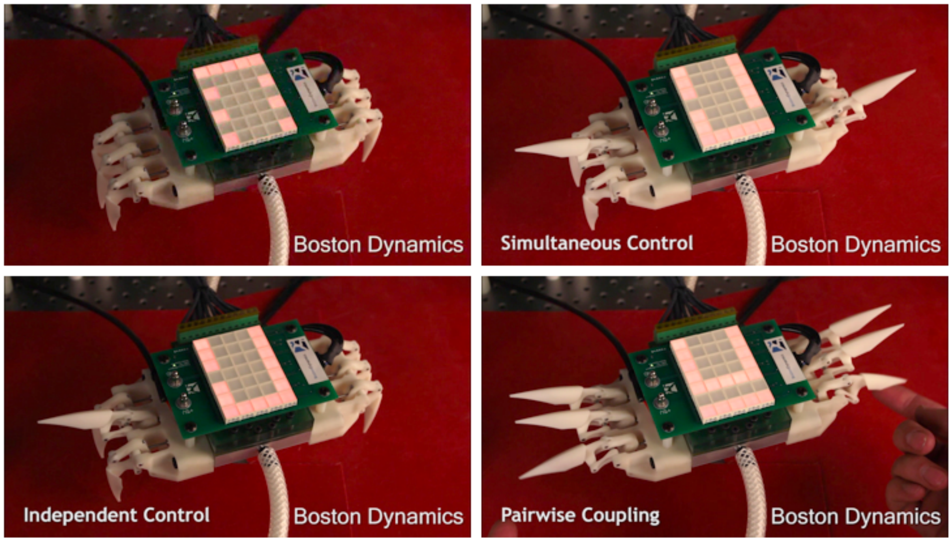



Figure 4: Snapshots from a demonstration video of the Programmable ER Manifold used to control the legs of a robot. An LED grid illustrates the current state of the electrodes in the manifold. These snapshots show several different states of the system.

**Technology demonstrations:**

To demonstration the effectiveness of the new valve technologies, ER valves were integrated into three mesoscale robotic platforms.

1. *Programmable ER Manifold a.k.a. "Disco Crab."* The simplicity of the mechanical components in an ER valve allow a multitude of valves to be utilized without a large increase in system complexity or cost. One concept for the use of a large number of valves is a programmable ER manifold, where the flow paths through a manifold can be controlled by applying various patterns to the electrodes. In this concept, one of the two electrodes that form an ER valve is divided up into a multitude of electrically isolated and individually addressable pixels. Pixels that are electrically excited at high voltage form chains within their area, stopping flow, while off pixels act as open passageways. By applying patterns to the grid, it is possible to re-route fluid lines from inputs to outputs within only a few tens of milliseconds.

   As a proof-of concept, we built a 35-pixel programmable ER manifold with eight fluid ports. One port supplied high pressure ER fluid, a second provided a low pressure output port, and the other six ports were connected to single-sided actuators. Actuators can be extended by connecting them through the manifold to the high pressure source, either individually, or simultaneously with others. Similarly, the actuators can be allowed to retract by connecting them to the low pressure return port. One new feature that this manifold enables is the ability to couple actuators together by connecting them together through the manifold. This passes forces and velocities from one actuator to another. The manifold concept allows any

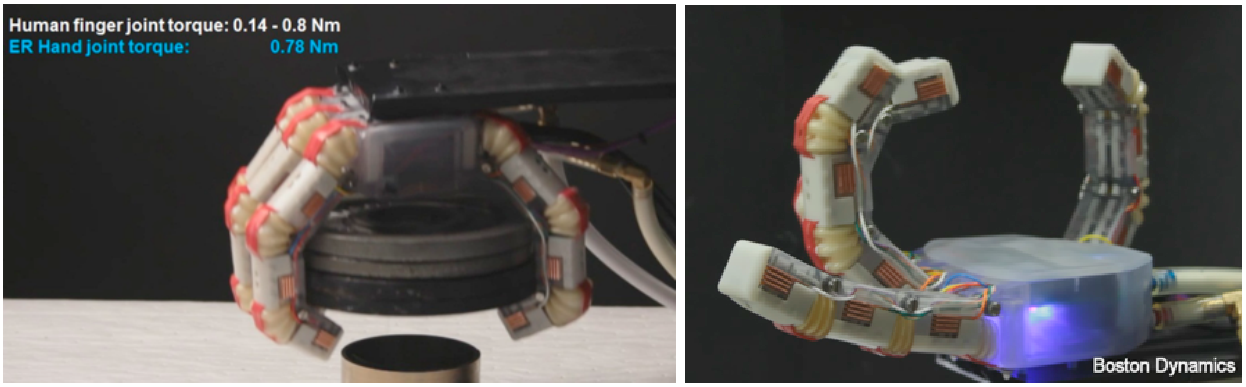



Figure 5: [Left] Snapshot of a video demonstrating the prototype lifting a 10 lb payload. [Right] Snapshot of a video demonstrating independent finger joint motions under ER Valve control at 45 psi and 3 kV.

input to be coupled with any other input, and simultaneous coupling is also possible as long as the paths do not cross.

To demonstrate this proof-of-concept, we attached a set of legs to the actuators and added an LED board on the top of the system whose state reflects the state of the pixels within the manifold. Red lit pixels, indicate that the pixel directly below is activated to high voltage, blocking flow (see Figure 4). The actuators were independently addressable, addressable in simultaneous combinations, and coupled to each other. In a video (video uploaded to the TFIMS website), we demonstrate independently addressable actuation, simultaneous actuation, coupling between two and three actuators and high speed switching.

2. *ER Hand Prototype.* To demonstrate a platform that has sufficient strength to do work at relevant scales, we constructed an ER robotic hand (see Figure 5). The prototype has 24 ER valves spread across four fingers with three joints each. These independently addressable joints are actuated by custom hydraulic bending bellows actuators capable of 0.78 Nm of torque, which is similar to the maximum torque of human finger joints. The switching electronics to control the ER valves was designed into the palm of the hand, with the capability of controlling 12 valves independently.

3. *ER tenacle.* As a demonstration of our new MINERVA technology, we designed and built an ER controlled tentacle camera. This tentacle is intended to provide a high degree-of-freedom camera arm for inspection on mobile robot platforms. We designed an H-bridge Minerva for the tentacle application and fabricated them in bulk. In the tentacle design the electronics to control the valves reside on the valves themselves, so only one high-voltage trace needs to be run along the length of the tentacle. In turn, this allows for a high number of valves in series in a snake-like configuration. The backbone of the tentacle is a flex circuit which both passes the electrical signals and serves as the inextensible spine. The MINERVAs are batch soldered along the flex circuit to form the full spine. Urethane shells are then bonded to both sides of the spine, sealing the chambers to create bellows actuators between each

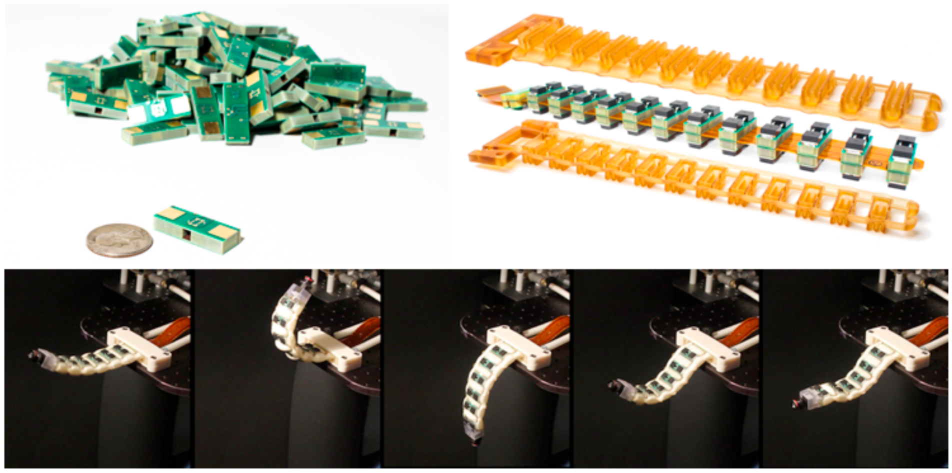


Figure 6: Batch produced MINERVAs for ER tentacle. Exploded view of spine construction. Urethane shells (top and bottom) create the flexible actuators and fluid paths, while valving is controlled by the MINERVAs along the spine (middle). Screenshots from a demonstration video of 6-segment tentacle motion. Large amplitude upward and downward bending is shown, followed by holding a specific curved shape while moving the camera segment to scan the camera up and down.

valve, and create the high and low pressure rails along the sides of the spine to provide the ER fluid a path to enter and exit the valves. An exploded view of the spine and shells, and images of the tentacle in motion can be seen in Figure 6.

**Other active material advances:**

1. *Tunable stiffness manipulator.* Hyper-redundant manipulators can be fragile, expensive, and limited in their flexibility due to the distributed and bulky actuators that are typically used to achieve the precision and degrees of freedom required. We have designed and constructed a manipulator that is robust, high-force, low-cost, and highly articulated without employing traditional actuators mounted at the manipulator joints. Rather, local tunable stiffness is coupled with off-board spooler motors and tension cables to achieve complex manipulator configurations. To test kinematics and motion planning for a tunable stiffness systems, we built a prototype arm composed of serial modules that can transition between rigid and flexible states via jamming. To select a viable granular filler, compression tests were conducted on several lightweight granular materials [1].

2. *Nonlinear tunable stiffness.* In applying tunable stiffness properties via jamming and unjamming of granular media in engineered devices, it is often desirable to maximize the strength of the jammed state (e.g., for load-bearing tasks) while maximizing the compliance of the un-jammed state. Unfortunately, the strength of the system is linearly proportional to the system's confining stress in most systems. Our challenge was to identify a granular system

that has a nonlinear inter-particle friction angle, that is higher in the jammed state than in the unjammed state. We achieve this by changing grain geometry via the system's confining stress. Specifically, a mixture of hard spheres and soft spheres exhibits the desired properties, as soft spheres can resist deformation to minimize inter-particle friction under low confining stress while they can deform to increase inter-particle friction under high confining stress. We determined the performance of systems with various mixing ratios of hard and soft spheres to determine design rules for optimizing a composite granular systems [2].

3. *MR Climber.* To demonstrate the use of active fluids for switchable adhesion, we have built a magnetorheological (MR) climbing robot. This form of controllable adhesion is unique in that it can be applied to a wide range of surface conditions (i.e. substrate types and roughnesses) and yield large clamping pressures without needing a ferrous substrate. In addition, this approach overcomes problems with dust and other surface contaminants. Actuated permanent magnets were chosen as the magnetic field sources for the robot [7, 8].

   To identify and quantify the primary modes of failure in extension we used a series of probe-tack tests. We find that at a critical stress (for Lord fluid on acrylic, 30 kPa) the failure mode switches from a cohesive failure (failure within the material) to an adhesive failure (failure at the interface). Practically speaking this implies that beyond a certain field, it is no longer advantageous to increase the field strength because the MR material is no longer the weakest link in the system [6, 3].

**Bibliography**.

[1] Nadia G. Cheng , Maxim B. Lobovsky, Steven J. Keating, Adam M. Setapen, Katy I. Gero, Anette E. Hosoi, Karl D. Iagnemma. "Design and Analysis of a Robust, Low-cost, Highly Articulated Manipulator Enabled by Jamming of Granular Media." 2012 IEEE International Conference on Robotics and Automation, St. Paul, MN, 2012.

[2] Nadia Cheng. *Design and Analysis of Jammable Granular Systems.* Ph.D. Dissertation, MIT, Department of Mechanical Engineering, 2013.

[3] Randy H. Ewoldt, Piotr Tourkine, Gareth H. McKinley, A. E. Hosoi. "Controllable adhesion using field-activated fluids." *Physics of Fluids*, **23**(7), 2011.

[4] Ahmed Helal, Bian Qian, Gareth H. McKinley and A. E. Hosoi. "Yield hardening of electrorheological fluids in channel flow." PREPRINT (available upon request) 2013.

[5] Bian Qian, Gareth H. McKinley, A. E. Hosoi. "Structure evolution in electrorheological fluids flowing through microchannels." *Soft Matter*, **9**(10), 2013.

[6] M. Watanabe, N. Wiltsie, A. E. Hosoi, K. Iagnemma. "Characteristics of Controllable Adhesion using Magneto-Rheological Fluid and its Application to Climbing Robotics." *Proceedings of the IEEE International Conference on Robots and Systems*, 2013.

[7] Wiltsie, N. *Controllably Adhesive Climbing Robot Using Magnetorheological Fluid.* MS Thesis, MIT, Department of Mechanical Engineering, 2012.

[8] Nicholas Wiltsie, Michele Lanzetta, Karl Iagnemma. "A Controllably Adhesive Climbing Robot Using Magnetorheological Fluid." Technologies for Practical Robotics (TePRA) Conference Proceedings, 2012.

**Appendixes**.

Details and supporting material can be found in previous quarterly progress reports and in the publications listed in the Bibliography.